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Focusing Magnets for HIF based on Racetracks

Nicolai N. Martovetsky and Robert R. Manahan

Abstract— Heavy Ion Fusion (HIF) is considered a promising path to a practical fusion reactor. A driver for a HIF reactor will require a large number of quadrupole arrays to focus heavy ion beams. A conceptual design, and trade off studies of the quadrupole array based on racetracks are presented. A comparison with a conventional shell magnet is given and advantages and disadvantages are discussed. A more detailed design of a single quadrupole for the High Current eXperiment (HCX) is presented and discussed.

Index Terms— Quadrupole, racetrack winding, gradient, harmonics

I. INTRODUCTION

IN the HIF reactor concept many heavy ion beams are accelerated in a linear accelerator and focused on a target, which ignites and produces fusion energy. A driver for the reactor has to be a reliable and economical device to make the concept a competitive source of energy. The requirements for the focusing power of the driver are very high, which makes the superconducting magnet *quadrupoles* the most attractive option for focusing the heavy ion beams in the accelerator.

The focusing *quadrupole* magnets have been developed and used successfully in the High Energy Physics (HEP) accelerators at FNAL, DESY, CERN for a long time. However, the new feature in the HIF drivers is that the magnets have to focus many tightly packed beams, which form a regular rectangular array. This main feature and the other features, like less stringent requirements for the field quality, short magnet lengths of the array, and a very strong requirement for a low cost result in a search for the most efficient concept for the focusing arrays.

There are several approaches to the solution of the problem. One approach is to try to utilize the technology developed for HEP for the shell magnets (i.e. when the windings are located on the cylindrical surfaces around the beam tube) and to expand it to the multi-beam arrays. The direct copying of the *quadrupoles* developed for ring accelerators provides a very good quality field [1]. But there is a concern that this approach may not be a very promising one, mainly from the economic standpoint [2]. An innovative fabrication process for the shell magnets is described in [2] which has a potential to reduce the production cost.

Another approach is to use *racetrack* windings to create an array, which is quite different from the traditional geometry for the accelerator magnets, but is usual for other applications. The *racetracks* have a long history of applications in electromotors, generators, wigglers and

undulators. In particle accelerators they are used mostly in non-superconducting magnets due to the simplicity of the winding, lower cost and the fact that the contribution to the magnetic field comes mostly from the iron poles, rather than the windings. For the superconducting magnets, where the conductors generate most of the field, the shell type magnets wound on a cylindrical surface were the primary line of development due to a higher efficiency of the superconductor use.

However, lately the *racetrack* winding has become an object of growing interest for the HEP colliders after introduction of the dual aperture accelerators [3-4]. The *racetrack* geometry appears to be very attractive both performance and cost wise, when the magnet flux can be shared between the two apertures. For the HIF focusing array, the flux is shared between many apertures for the beams and the concept of the *racetracks* seems to be attractive as well.

Another reason for interest towards the *racetrack* windings is the desire to reduce training and degradation in the superconducting magnets. Training and degradation in the magnets result in inability to reach the designed parameters until after many quenches, and in inability to reach the conductor properties even after many charges. The collared shell magnets have relatively complex structures with very tight tolerances to support the forces and eliminate micro movements of the superconductor, which are responsible for training and degradation. But even the best-developed methods of the winding support do not eliminate training and degradation completely.

There is a hope that due to a simpler magnet structure, the *racetrack* windings will experience much less degradation and training in comparison with the collared shell magnets.

This paper discusses a concept of the focusing arrays on the basis of the *racetracks* and discusses advantages and disadvantages of the concept.

II. HIF FOCUSING ARRAY

A. Requirements

Requirements for the HIF driver are still under study and not finalized. Preliminary, the HIF focusing arrays for the induction accelerators should produce a *quadrupole* field with an integrated error of better than 0.1% at 80% of the radius of the beam tube. Also, there should be a very low stray field outside the array, since there are ferromagnetic

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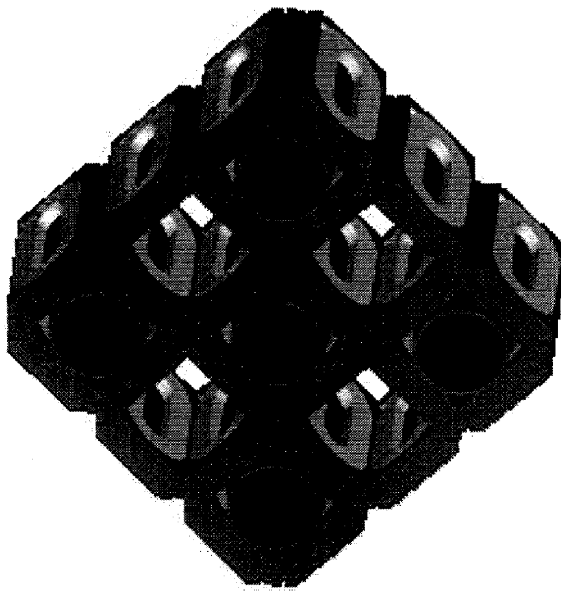


Fig. 1 A 3x3 fragment of the HIF focusing array

elements in the accelerating sections of the HIF driver. Axially the arrays should have very little wasted space, which requires a shortest possible end part of the *racetrack*. The maximum field in the winding is foreseen to be in the range of 4-6 T and the array is required to produce the highest possible magnetic field *gradient*.

Since several thousands of the arrays will be needed for the HIF driver, one of the most important requirements would be a low production cost of the magnets.

B. Conceptual design description

A view of the 3x3 fragment of the focusing array with the *racetrack* windings is shown in Fig.1. Every other beam tube is removed for clarity. The array shown in Fig. 1 is assembled from cells. A cell is assembled from the integrated double-sided *racetracks*, mounted in the coil forms. The *racetracks*, which two adjacent cells, are mounted in each coil holder. A single cell of the array is shown in Fig. 2. Such an arrangement makes the interface between neighboring cells much easier than in the shell type arrangement. Because of that simplicity and a very effective use of the structural material to support the electromagnetic forces, the *racetrack* array can be made very compact.

The array is assembled from identical elements, which makes it very attractive for mass production.

1) Field quality considerations

To generate a good quality *quadrupole* field the *racetracks* are designed to approximate the classical linear current distribution in a square cell. Fig. 3 shows an ideal linear current distribution in a cell of an infinite array which generates a pure *quadrupole* field and its approximation with the *racetrack* windings. This deviation from the ideal current distribution creates some error field *harmonics*, which need to be cancelled out or greatly suppressed. This task is similar to shell magnet design optimization, when appropriate



Fig.2. A cell of the quadrupole array and an individual integrated racetrack

spacers allow reducing the error field to an acceptable level. In this respect, *racetrack* optimization is no more difficult than for shell magnets.

One of the drawbacks of the *racetrack* current distribution shown in Fig.3 is that the corners, which ideally should carry the highest current density, are not available for the windings, since the corners are used for the structural interfaces with the neighbors. This problem is not significant for large bore beam tubes (80-100 mm diameters), but becomes a factor at smaller apertures.

For small aperture magnets the geometry of the *racetrack* magnets could be modified to place the conductor in the corners and move the interface between two adjacent *racetracks* from the corners. That would lead to two basic elements, instead of one, to build a *quadrupole* cell.

2) Supporting electromagnetic forces

When the array is energized, significant electromagnetic forces are generated, which need to be supported by the structure to prevent possible quenching and change of the geometry, which may distort the field. Fig. 4. Illustrates the forces in the shell type and the *racetrack* type magnets (one quadrant of the cross section is shown only). The distribution of forces in the magnet in an array is significantly different from that in a stand-alone *quadrupole*.

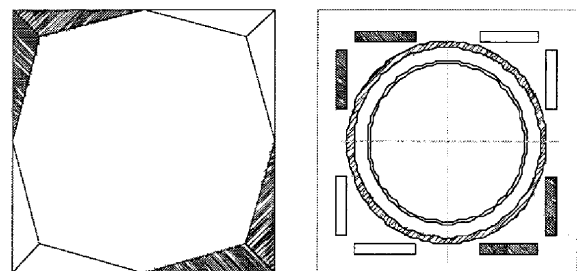


Fig.3. Ideal current distribution in a cell of an infinite array and its approximation with the *racetrack* windings

In a stand-alone *quadrupole*, there is a component of the force directed inward (see Fig.4 a and b). A *racetrack*

configuration is not very efficient to oppose this component, since the forces tend to separate the winding from the *racetrack* structure. The shell magnet geometry is very convenient for the force distribution and a hoop structure and the wedges between the winding packs on the collars support these forces very efficiently.

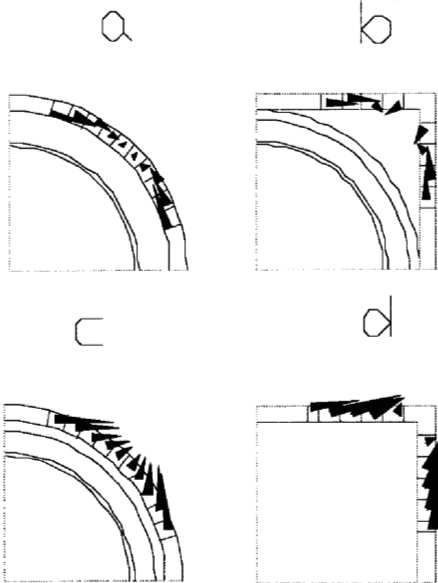
In contrast to the single *quadrupole*, in the array configuration, the forces generated in the windings are easily supported in the *racetrack* configuration shown in Fig.2. Due to the symmetry, all out-of-plane forces in the *racetrack* are cancelled within the double-sided *racetrack* structure, which makes the coil holder react the in-plane forces only. This is the most efficient use of the structural material.

Also, such a design is convenient for giving a prestress to the winding pack from inside the *racetrack*, using wedges. Ensuring an adequate prestress is considered one of the most important measures to reduce degradation and training in the coils.

The shell type magnets use collars and/or shells or shrink fit cylinders [2] to contain the electromagnetic forces and to provide a prestress on the winding during assembly. Since utilization of the structural material in the *racetrack* cell is more efficient, the *racetrack* configuration can be made more compact.

C. Comparison between the shell and the *racetrack* quadrupole arrays

To compare performance of two different concepts we analyzed three *quadrupole* cells for infinite HIF array. All cells were assumed to have 120 mm-diameter beam apertures. The shell magnet cell unit occupies 200x200 mm space. We compare it to two *racetrack* cells – one with the same size cell of 200x200 mm and the other with 180x180 mm size cell. The cross sections of the compared 200 mm shell and 180 mm *racetrack* cells are shown in Fig.5. Table 1 gives



the
Fig. 4 Forces in the shell magnet cell and a *racetrack* cell for an infinite array: a) shell magnet single quadrupole, b) *racetrack* quadrupole, c) shell quad cell in an infinite array, d) *racetrack* quad cell in an array

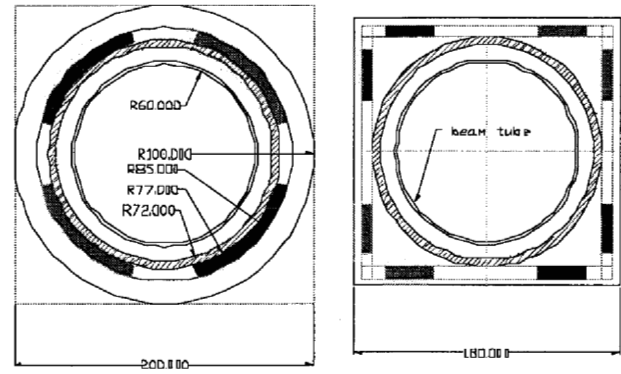


Fig. 5. Comparison between a shell quadrupole and a *racetrack* quadrupole for infinite array

comparison between the main parameters of the *quadrupoles*.

For the trade off study we assumed that the thickness of the winding is the same. We designed the windings with no gaps. We selected the peak field in the winding to be around 4.5-5 T. We designed the 2D geometry for all options in such a way that the main error field component, the dodecapole component a_6 , would be zero.

TABLE 1. COMPARISON OF THE SHELL AND RACETRACK QUADRUPOLES IN ARRAY

Harmonics @R= 48 mm	shell, 200 mm cell	Racetrack, 200 mm cell	Racetrack, 180 mm cell
a_2 , T	2.20	1.73	2.01
a_{10} , T	-5.75E-03	-3.50E-03	-4.01E-03
I total, A	1.62E+05	1.35E+05	1.30E+05
Bmax, T	4.51	4.51	5.12
Gradient, T/m	45.78	36.08	41.91
Grad/I*1e5	28.35	26.69	32.24

Table 1 shows that in array, the shell magnet with the same cell size is still more efficient than the *racetrack* cell, since the conductor is closer to the aperture. However, the difference is much smaller than that for a single *quadrupole* magnet. If a slightly smaller *racetrack* cell can be built due to a simpler interface and less structure, the performance of the *racetrack* is very competitive with the shell magnet. The error field can be maintained low and the *gradient* per unit of superconductor (or current) is even a little higher for the *racetrack* cell than for the shell cell in our study.

D. Termination of the infinite array with *racetrack* windings

The HIF driver will have 21-100 beams, which translates into 5x5 to 10x10 arrays with possible modifications to the corner cells. If nothing is done at the periphery of the array, the outside row of cells will have too poor of a field quality to be used for the beams and this is unacceptably inefficient. To maintain a high quality *quadrupole* field in all cells of the array, compensation windings have to be used on the periphery of the array. The generic approach to the termination of the finite array to simulate the infinite array is described in [5]. This approach eliminates the stray field outside the magnet and makes the field in all cells purely *quadrupole*. The implementation of this approach was studied for the shell magnets and it was found that it requires an additional space of half of the cell size around the array and rather complicated geometry windings to simulate an infinite array [5]. Our studies on the example of 3x3 array

showed that the racetrack array could be easily terminated with auxiliary *racetrack* windings to cancel out the stray field and to maintain a high quality field in all the cells of the array. Thus, termination of the *quadrupole* array is possible without a new type of windings and is easier than termination of the shell magnets array.

E. Conductor selection

The *racetrack quadrupoles* have a wide selection of the superconductor. Any conductor used for the shell magnet can be utilized in the *racetracks*, however from the mechanical standpoint it would be beneficial to use a monolithic conductor with a rectangular cross section. That will allow the creation of a geometrically very well defined winding pack with a high modulus and very low deflections, thus minimizing the probability of a quench. Monolithic conductors are acceptable for HIF application since it is essentially a DC device and AC loss is not a factor. A monolithic conductor can be made from a regular multifilamentary or APC round and twisted conductor by rolling it down to a rectangular cross section. The aspect ratio of the rectangular conductors can be up to 1:7 before a noticeable anisotropic effect of 30% takes place. This anisotropic effect results in the decrease of the critical current density in the conductor when its wider side is oriented perpendicular to the magnetic field [6]. Simultaneously, the critical current increases if the conductor is oriented with its wider side parallel to the magnetic field. In our application this effect of anisotropy is not that essential and may even be beneficial, since the undesirable magnetic field component is present only in the low field areas, while enhancement of the critical current in the parallel high field provides a larger operational margin. Such a conductor is a much more economic option than a traditional Rutherford cable or other cables.

III. HIGH CURRENT EXPERIMENT (HCX) QUADRUPOLE WITH RACETRACK COILS

A collaborating team of LBL, PPPL and LLNL is building a High Current Experiment to validate many critical issues for developing a HIF Integrated Research Experiment, which will employ superconducting focusing arrays. The HCX will use a single beam and the Second Phase of the HCX will use the superconducting focusing *quadrupole*.

To advance the design of the *racetrack quadrupole* and to study the potentials of the approach we designed a *quadrupole* for a single beam, and we are in the process of prototype work.

The concept of the *racetrack quadrupole* for the array is integrated into a single beam *quadrupole*. Although the theoretical efficiency of the *racetracks* for a single *quadrupole* is less than the efficiency of the shell magnets, a high current density in the winding pack and a relative simplicity of the design make the *racetrack* geometry

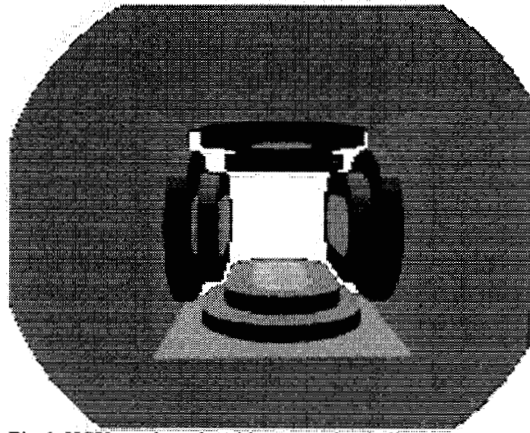


Fig.6. HCX quadrupole with racetrack windings

competitive against the shell type magnets. The schematic representation of the HCX *quadrupole* is shown in Fig. 6. In contrast to the array where the ferromagnetic shield does not improve the magnet performance, the iron yoke and the ferromagnetic inserts in the *racetrack* windings improve the *gradient* of the *quadrupole* significantly and bring the efficiency of the *racetrack* quad closer to the efficiency of the shell magnet [7].

IV. CONCLUSIONS

The *racetrack* winding is a promising concept for the HIF focusing arrays due to the following features:

- Efficient support structure and stress management
- Simple interfaces between cells
- Convenient assembly of the array
- Interchangeable modules
- Attractive for mass production

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